

# Formation of Optimum Index Profile in High-Bandwidth Graded-Index Plastic Optical Fiber and Its Modal Analysis

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## Abstract

It is clarified that the interfacial-gel polymerization technique is the promising fabrication method to form the optimum refractive index distribution which offers the highest bandwidth of the graded-index plastic optical fiber (GI POF). The optimum refractive index profiles of both poly methyl methacrylate (PMMA) based and perfluorinated (PF) polymer based GI POFs were theoretically calculated by taking all dispersion factors (modal, material and profile dispersions) into consideration. Obtained index profile by optimized polymerization condition was much close to the ideal one theoretically calculated and had no explicit index perturbation which existed in the silica based multimode fiber (MMF). The small modal dispersion property of the high bandwidth GI POF was experimentally confirmed by measuring the effect of propagating mode characteristics. Furthermore, the great advantage of the PF polymer based GI POF in the bandwidth was clarified. The PF polymer based GI POF link has the possibility of achieving the higher bit rate than even silica based MMF link, since the material dispersion of the PF polymer is lower than those of silica and other polymer materials.

## Introduction

Many forms of communication systems have appeared over the years with increasing demand of high-speed access to Internet. High-bandwidth GI POF is currently one of the promising candidates for such high-speed data transmission medium. Great interests in the characteristics of the GI POF have triggered to make efforts on its bandwidth analysis. Recently, more interests have been focused on the bandwidth characteristics of the GI POF. It is well known that the bandwidth characteristics of the multimode fiber, including POF, is dominated by the modal dispersion which strongly depends on the refractive index profile in the core. In the case of the silica based multimode fiber (MMF) fabricated by typical MCVD method, rippled refractive index profile perturbation was observed due to the stepwise concentration difference of the  $\text{GeO}_2$  in each deposited layers. Therefore, the modal dispersion of the silica based MMF has not necessarily been minimized, and achieved bandwidth has been much lower than that expected. On the other hand, it is both experimentally and theoretically clarified that the refractive index profile of the GI POF formed by the interfacial-gel polymerization process can be close to almost optimum. The index profile of the GI POF can be controlled by the polymerization reaction rate. For forming the refractive index distribution in the plastic materials, the optimum index profile was theoretically calculated by considering not only modal but also the other factors affecting the bandwidth characteristics of the GI POF. In addition, it was theoretically confirmed that the lower material dispersion of the perfluorinated (PF) polymer based GI POF enabled higher bit rate transmission than silica based MMF even at short wavelength as  $0.85\text{-}\mu\text{m}$  by controlling the index profile of the GI POF to optimum.

## Optimum Index Profile Design and Formation by Interfacial-Gel Polymerization Technique

In order to obtain the highest bandwidth GI POF, the optimum index profile of the GI POF was theoretically estimated with using WKB method. When the refractive index distribution of the GI POF is approximated by well known power-law form described by eq. (1), the impulse response function width can be analytically estimated.

$$n(r) = n_1 \left[ 1 - 2\Delta \left( \frac{r}{a} \right)^g \right]^{\frac{1}{2}} \quad 0 \leq r \leq a \quad (1)$$

where,  $n_1$  and  $n_2$  are refractive indexes of core center and cladding, respectively,  $r$  the distance from the core center,  $a$  the core radius, and  $\Delta$  is the relative index difference. The parameter  $g$  is called as the index exponent which can determine the refractive index profile. During the calculation process, the material dispersion of the plastic material was taken into consideration. The material dispersion is the dispersion factor induced by both wavelength dependence of the refractive index of plastic and finite line width of light source.

The wavelength dependence of the refractive index of plastics was directly measured. It is widely known that the optimum index exponent ( $g_{\text{opt}}$ ) is almost 2.0 when only modal dispersion was taken into account. On the other hand, by considering the material dispersion, the  $g_{\text{opt}}$  of the PMMA based GI POF was approximately 2.4 at 650-nm wavelength that is one of the optical windows of PMMA-based POF.

The GI POF was obtained by the heat-drawing of the graded-index preform. We have proposed the interfacial-gel polymerization technique as the fabrication method of the GI POF [1], [2]. Since the refractive index profile of the GI POF is formed during the polymerization reaction of the core region, the polymerization reaction rate plays an important role to control the refractive index profile. The index profile of the GI POF was controlled by changing the kind and concentration of polymerization initiator and chain transfer agent, and polymerization temperature.

The experimentally measured refractive index profiles of the GI POFs are shown in Fig.1, comparing with the approximated curves by eq. (1). The refractive index profile of Fiber 1 was obtained under the almost optimized polymerization condition to form the ideal index distribution.

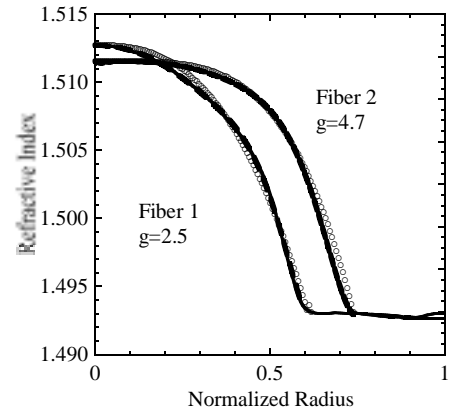


Fig. 1 Refractive index distribution of PMMA based GI POF. Plots: approximated curve by power-law form.

### Bandwidth Property of the GI POF

The bandwidth characteristic of the GI POF was investigated by a time-domain measurement method. Figures 2 and 3 show the results of the output pulse from the GI POFs whose index profiles are shown in Fig. 1. When the index profile is deviated from the optimum (Fiber 2), significant output pulse broadening is observed, while little pulse distortion is observed in the GI POF having almost ideal index profile (Fiber 1). The bandwidths of the GI POFs shown in Figs. 2 and 3 were analytically estimated with using WKB method. These results were summarized in Table 1.

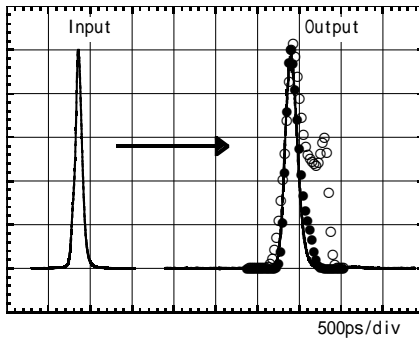


Fig.2 Bandwidth property of 100-m GI POF (Fiber 1) solid line: measured result Estimated waveforms ○: all modes were assumed to be uniformly launched ●: DMA was considered.

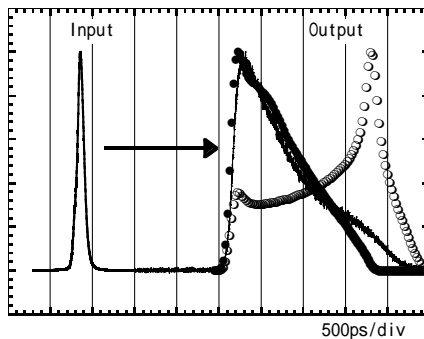


Fig.3 Bandwidth property of 100-m GI POF (Fiber 2) solid line: measured result Estimated waveforms ○:all modes were assumed to be uniformly launched ●: DMA was considered.

Table 1

Comparison of bandwidth of 100-m GI POF

	Measured Bandwidth	Calculated Bandwidth	
		Only modal dispersion considered	All dispersions considered
Fiber 1	2.6 GHz	1.1 GHz	2.2 GHz
Fiber 2	0.44 GHz	0.29GHz	0.38GHz

It is obvious that if only modal dispersion is taken into account, the estimated bandwidth is much less than the measured one, whereas a good agreement is observed if the material and profile dispersions were considered. There were several reports that said such a high bandwidth was not theoretically achieved, and that the origin of the high bandwidth of the GI POF was the strong mode coupling effect. However, in most previous reports, since only modal dispersion was considered in theoretical calculation of the bandwidth, such a disagreement was supposed to be caused.

### Propagating Mode Characteristics

In order to clarify the bandwidth potential of the GI POF prepared by the interfacial-gel polymerization process,

the propagating mode characteristics were precisely analyzed. First, the group delay of the propagating modes in the GI POF was numerically calculated. In this process, the refractive index profile of the GI POF was approximated by the ten terms polynomial form instead of power-law form. In this case, the Maxwell's wave equation has to be numerically solved to obtain the propagation constant of the mode. After calculating the propagation constant, the impulse response of the GI POF was estimated. In this calculation process, the material and profile dispersions were also taken into consideration. Calculated output pulse waveforms are shown in Figs. 2 and 3 by plots. It is obvious that when all the modes were assumed to be uniformly launched, slight disagreement is observed between the measured and calculated (open circle) waveforms. However, it is theoretically verified that output pulse broadening is much small in Fiber 1. The origin of the disagreement was analyzed by measuring the differential mode delay (DMD) of the GI POF. In the DMD measurement, optical pulse is coupled into the GI POF via a 1-m single mode silica fiber in order to launch a specified mode group of the GI POF. By shifting the position of the single mode fiber butted to the GI POF from the core center to the periphery, each mode from the low order to high order can be independently launched. The results of Fiber 2 are shown in Fig. 4 comparing with theoretically calculate DMD.

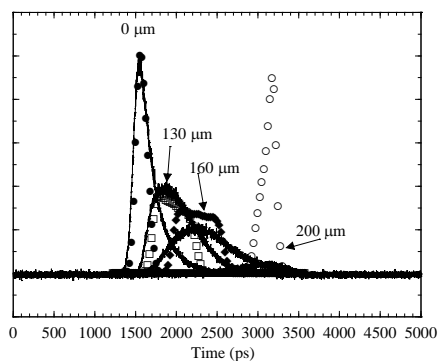


Fig.4 Measured (solid line) and calculated (plots) DMD of 100-m Fiber 2. Distances are the shifted position of SM fiber from the core center

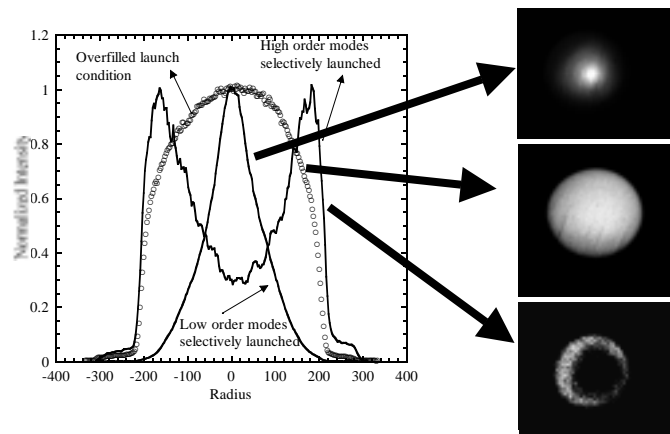


Fig.5 NFP of 100-m Fiber 1 when all the modes and specified mode group were launched.

It is noteworthy that each mode has its own delay time and the estimated delay time (shown by plots) well agreed with measured results. It was revealed from Fig. 4 that the calculated output intensity of the high order mode is much larger than that measured, although its delay time is precisely predicted. Simultaneously, the output near-field patterns (NFP) made by each modes were measured during the DMD measurement, and those are shown in Fig. 5. It is shown that much small spot compared with core diameter was formed by the low order mode, and ring like pattern which is typical for high order modes was also observed when only high order modes were selectively launched.

In the calculated output waveforms (open circle) shown in Figs. 2 and 3, two strong peaks are observed when all the modes were assumed to be uniformly launched (overfilled launch), which causes disagreement between the calculated and measured waveforms. Therefore, the differential mode attenuation (DMA) was experimentally measured for these POFs and the measured DMA was taken into consideration in the calculation of output waveforms. The calculated waveforms are also shown in Figs. 2 and 3 by closed circle. It is noteworthy that if the differential mode attenuation was taken into account, the second peak existed in the calculated waveforms assuming overfilled launch (open circle) is completely disappeared, and an excellent agreement between measured and calculated (close circle) waveforms is observed. In addition to the above results, we investigated the fiber length dependence of the far-field output patterns (FFP) and strong launch condition dependence on FFP was observed. Therefore, it could be concluded that there was little mode coupling effect on the bandwidth of 100-m length GI POF, and the high bandwidth of the GI POF was attributed to well optimized refractive index profile and the differential mode attenuation.

### High Bit Rate Transmission by GI POF

It was confirmed in the above section that the order of GHz bandwidth could be achieved by the GI POF having optimized index profile. Currently, the PMMA based GI POF is expected to be one of the physical media for high-speed home network, where more than 500 Mb/s, 50-m transmission is required. In this paper, we clarify

that more than GHz of fiber bandwidth provides a large freedom in POF link design, because link power penalty is much sensitive for the fiber bandwidth. The link power penalty was experimentally measured by constructing 50-m GI POF link with 500Mb/s optical transceiver (650-nm wavelength). As the test fiber, the GI POFs having different bandwidth from 300MHz to 2.48GHz for 50m were adopted, and the relation between the fiber bandwidth and power penalty was evaluated. The results are shown in Fig. 6. It is noteworthy that even if the GI POF has 860 MHz of bandwidth, which seems sufficient for 500 Mb/s transmission, about 1.3 dB of the link power penalty was observed, while the GI POF having higher than 2.5 GHz of bandwidth shows no power penalty. Observed eye diagrams are also shown in Fig. 6 in the case of GI POFs having 2.48 GHz and 392 MHz. Bandwidth limitation is clearly observed in eye diagram of 392MHz GI POF link. Therefore, it was found that even for several hundreds Mb/s transmission, more than GHz of bandwidth should be provided by the GI POF.

On the other hand, PF polymer based GI POF is expected in the field of local area network (LAN) as an alternative medium to silica based MMF. Silica based MMF is adopted as the physical medium of Gigabit Ethernet, the worldwide standard of LAN protocol, and currently it is under discussion to adopt it to 10Giga Ethernet. Although the fiber should have much high bandwidth for realizing such high-speed network, silica based MMF has the problem in its dispersion. The index profile perturbation typically observed in MMF prepared by MCVD method increases the modal dispersion. On the other hand, the possibility to precisely control the index profile by the interfacial-gel polymerization process allows the GI POF to have much lower modal dispersion than MMF. The bandwidth potential of the PF polymer based GI POF was calculated with using WKB method by considering all the dispersion factors. The material dispersion of the PF polymer was directly obtained by measuring the wavelength dependence of the refractive index of polymers. The calculated bandwidth property of the PF polymer was shown in Fig. 7. Since VCSEL emitting at 0.85- $\mu$ m wavelength is expected to be a high-speed, low-cost light source in LAN, the index profiles of both PF polymer based GI POF and silica based MMF were optimized at 0.85- $\mu$ m in calculation. As shown in Fig. 7, the possible bit rate of PF polymer based GI POF is much higher than silica based MMF in wide wavelength range from 0.85 to 1.3- $\mu$ m because of its small material dispersion. Furthermore, it is noted that by combining high bandwidth PF polymer based GI POF and VCSEL having narrow spectral width, more than 10 Gb/s for 1 km transmission is possible, which cannot be achieved by the silica based MMF.

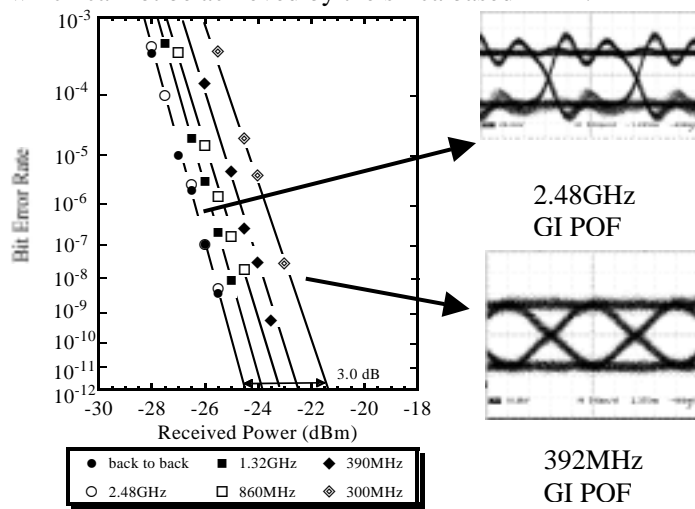


Fig. 6 Bit error rate characteristics and eye diagrams of 500 Mb/s, 50-m GI POF link.

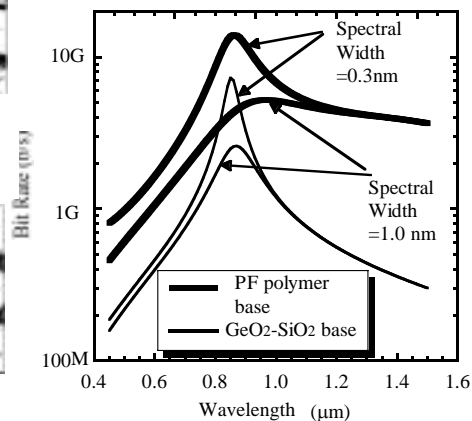


Fig. 7 Calculated bit rate potential of 1-km PF polymer based GI POF link compared with that of silica based MMF link

## Conclusion

It was clarified that GHz order of the bandwidth was inevitable even in short distance data communication. The GI POF whose index profile is precisely controlled to the optimum, is expected to be the promising candidates of the physical media for such high bit rate data link. In addition to the small modal dispersion, the low material dispersion of the PF polymer will open the way for great advantage in the high-speed optical data link.

## References

1. Y. Koike, T. Ishigure, and E. Nihei, *IEEE J. Lightwave Technol.*, **13**, 1475, (1995)
2. T. Ishigure, E. Nihei, and Y. Koike, *Appl. Opt.* **35**, 2048, (1996)